# A computational perspective on social attachment

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# A computational perspective on social attachment

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ABSTRACT

Humans depend on social relationships for survival and wellbeing throughout life. Yet, individuals differ markedly in their ability to form and maintain healthy social relationships. Here we use a simple mathematical model to formalize the contention that a person's attachment style is determined by what they learn from relationships early in life. For the sake of argument, we therefore discount individual differences in the innate personality or attachment style of a child, assuming instead that all children are simply born with an equivalent, generic, hardwired desire and instinct for social proximity, and a capacity to learn. In line with the evidence, this innate endowment incorporates both *simple bonding instincts* and *a capacity for cognitively sophisticated beliefs and generalizations*. Under this assumption, we then explore how distinct attachment styles might emerge through interaction with the child's early caregivers. Our central question is, how an apparently adaptive capacity to learn can yield enduring maladaptive attachment styles that generalize to new relationships. We believe extensions of our model will ultimately help clarify the complex interacting mechanisms – both acquired and innate – that underpin individual differences in attachment styles. While our model is relatively abstract, we also attempt some connection to known biological mechanisms of attachment.

## 1. Introduction

Humans depend on social relationships for survival and wellbeing throughout life (Bartholomew, Henderson, & Dutton, 2001; Blanchard, McKittrick, & Blanchard, 2001; Bowlby, 1969; Cohen & Wills, 1985; Harlow & Suomi, 1970; Hazan & Shaver, 1987; Heinrichs, Baumgartner, Kirschbaum, & Ehlert, 2003; Insel & Young, 2001; Kirschbaum, Pirke, & Hellhammer, 1993; Panksepp, Nelson, & Bekkedal, 1997; Prior & Glaser, 2006; Sapolsky, 2005). Early social bonding is largely controlled by myopic, hard-wired instincts which are presumably only optimal over evolutionary time (Bartholomew et al., 2001; Bowlby, 1958, 1969). It is unclear how such instincts relate to the following apparent sub-optimalities of 'goal-directed' or instrumental bonding. First, children seek social proximity to their primary caregiver, even when this caregiver does not reliably reinforce – and may punish - these advances (1969, Bartholomew et al., 2001; Bowlby, 1958). Second, early adverse relationships can undermine the formation of later, potentially rewarding, relationships (see also, e.g., Edelstein & Shaver, 2004). Our puzzle is how a child's attachment style develops early in life, and why apparently maladaptive styles might emerge and persist into adulthood in cognitively sophisticated individuals (for related work, see e.g., Callaghan & Tottenham, 2016, see also Frankenhuis & Del Guidice, 2012; Meacham & Bergstrom, 2016; Trimmer, Higginson, Fawcett, McNamara, & Houston, 2015).

Here we model bonding instincts as *Pavlovian responses* - e.g. social approach, inhibition and avoidance - and assume these instincts co-exist with more sophisticated, goal-directed social cognitions (Amat et al., 2005; Domjan, Cusato, & Villarreal, 2000;

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Locurto, 1981; Rosenthal & Matthews, 1978; Seligman, Maier, & Solomon, 1971; Seligman, 1972; Williams & Williams, 1969). By direct analogy to Pavlovian feeding behavior (Dayan, Niv, Seymour, & Daw, 2006), our key assumption is that this instinctive bonding behavior can be triggered by learned generalizations, and not just external unconditioned social cues (such as the smell of the mother). Learned expectations and unlearned action programs, while seemingly antithetical, are easily bridged via the concept of an agent's internal (scalar) "expected value" of reward or punishment. On the one hand, this scalar reflects learned predictions about the current state. On the other, it can trigger hard-wired or unlearned Pavlovian response programs, such as instinctive social approach. (Note that this role for expected value is qualitatively different from – and may conflict with – a role for expected value in goal-directed choice among a set of non-instinctive actions, a.k.a. utility maximization.) This hypothetical chain of causation implies that, whenever a person has acquired a generalized expectation about the available social reward or punishment, a generalized behavioral disposition will follow closely behind. In this way, we argue that an emergent "attachment style" - a disposition for social approach/withdrawal - may reflect tonic excitement of hard-wired social instincts by generalized social predictions.

We show that persistent, self-defeating attachment styles can arise naturally whenever sophisticated beliefs do indeed activate or inhibit the expression of simpler and instinctive bonding behaviours. Our account therefore attempts to reduce the development of attachment style to well-documented properties of Pavlovian learning, while at the same time acknowledging the central role of "internal mental models" of the social environment. Our work does not preclude that affect plays an important proximal role in behavior. In fact, the concept of value, which we use to link cognitive generalizations and "affective" unlearned actions, might relate directly to experienced "valence" (affective or subjective).

In the following section, we provide a brief introduction to the rationale of computational models of social bonding. Then, we give some theoretical background on the behavioural neuroscience of bonding and describe the details of our model. The model itself demonstrates how an experience-dependent Pavlovian approach – in response to anticipated reward – and Pavlovian inhibition – in response to uncontrollable "helpless" punishment - might result in generalized, non-instrumental attachment styles in cognitively sophisticated humans (Bartholomew et al., 2001; Hazan & Shaver, 1987). We view adult-child (Field, 1996) and pair (Moore, 1985; Renninger, Wade, & Grammer, 2004) bonding as a repeated interaction in which one or both parties come to seek out proximity and we examine the learning dynamics of this preference. We focus on Adult-Child relationships and refer to the partners as 'Adult' and 'Child'. Our model examines bonding behavior from the child's perspective. It posits that experience-dependent but evolutionarily pre-specified behavioral impulses to approach or withdraw increasingly limit the child's ability to adapt to the Adult's policy and thereby prevent the child from achieving their own social goals. In this way, our model caricatures how early experience with an adult, or series of adults, can adversely shape the child's own future bonding style (Hazan & Shaver, 1987).

We relate our findings to empirically-reported differences in the developmental trajectory of attachment behavior across children, in particular their signaled need for proximity and autonomy/exploration (e.g., Ainsworth, 1985; de Wolff & van Ijzendoorn, 1997; Cummings & Cummings, 2002; Bigelow et al., 2010). As with Callaghan and Tottenham (2016), Dridi and Akçay (2018), Frankenhuis, Panchanathan, and Barto (2018), and Singh, Lewis, Barto, and Sorg (2010), our paper provides an opportunity to bridge different fields, such as reinforcement learning and evolutionary developmental psychology / behavioral ecology. We offer a novel, computational perspective on the dynamics underlying the emergence of a secure attachment style in children with a history of prior neglect. We therefore hope that the model adds to recent research that attempts to understand the potential of positive, or sensitive, foster care to remedy insecure attachment in maltreated children (Joseph, O'Connor, Briskman, Maughan, & Scott, 2014). On first reading, most readers may want to skim over Sections 2–3.2, which elaborate some contextual and mathematical details. Our core argument and results are found in Section 3.3–5.

## 2. Computational models of social attachment

"Computational" models in psychology (Marr, 1982) aim to explain the cognitive challenges an environment poses to individual fitness in relatively abstract terms. Typically, the author will derive the *ideal* solution to this challenge, which then serves as a null hypothesis for how humans solve the problem. Such models are commonplace in developmental theories of language, theory of mind, concept learning and neonate reasoning (Perfors, Tenenbaum, Griffiths, & Xu, 2011; Téglás et al., 2011). This modeling perspective has been extended to study apparently 'irrational', 'hot' or 'affective' processes. Such extensions typically assume that evolution has furnished multiple, potentially competing, solutions which may conflict in the same individual (Dayan & Niv, 2008; Dayan et al., 2006). Here we apply this latter idea to the socio-emotional challenges of social bonding as follows.

Goal-directed animal behaviour can be contrasted with more primitive impulses studied in the tradition of Pavlov (Pavlov & Anrep, 2003). In the field of human social cognition, most schemes divide social information processing into relatively-automatic versus goal-directed (Adolphs, 2009). Yet despite its importance to normal and clinical behaviour, there is currently no quantitative model of how instincts might support or undermine goal-directed social behaviour. Species-specific instincts – while evolutionarily optimal in some way - have long been known to interfere with optimal choice in non-social settings (Domjan et al., 2000; Locurto, 1981; Rosenthal & Matthews, 1978; Williams & Williams, 1969). Yet parent–infant and male–female ('pair') attachment behaviours are also instinctive and conserved across many mammalian species (Bretherton, 1985; Insel & Young, 2001; Young, Lim, Gingrich, & Insel, 2001), presumably because they increase Darwinian fitness (Bowlby, 1969; Prior & Glaser, 2006). While such behaviours are often complex (Ainsworth, 1979; Harlow & Suomi, 1970) they characteristically involve a behavioural preference for physical proximity to a social partner or carer, which is assumed to be the 'set-goal' of an 'innate attachment behavioural system' (Bretherton, 1985). If proximity-seeking reflects an involuntary instinct, it should persist even when it contradicts the individual's own goals. We look to this mechanism to explain robust persistence in both punishing (Ainsworth, 1979) and rewarding relationships. Because

proximity-seeking is known to depend on both social rewards and punishments (Ainsworth, Blehar, & Waters; Harlow & Suomi, 1970; Karen, 1994) we consider these in turn.

## 3. The model

### 3.1. Background: the behavioural neuroscience of bonding

Dopaminergic and Oxytocinergic systems are implicated in normal parent-infant partnerships (Baskerville & Douglas, 2010; Strathearn, Li, Fonagy, & Montague, 2008; Strathearn, Fonagy, Amico, & Montague, 2009). General hormonal changes during pregnancy facilitate social learning (Pearson, Lightman, & Evans, 2009; Kinsley et al., 2008). Oxytocin's effect on rat maternal care likely reflects modulation of dopaminergic prediction-error learning (Schultz & Dickinson, 2000; Schultz, Dayan, & Montague, 1997). (Oxytocin also increases social approach in rats (Pedersen, Ascher, Monroe, & Prange, 1982) and social learning in rat pups (Nelson & Panksepp, 1996). In humans, oxytocin receptors concentrate in some dopamine regions (substantia nigra, globus palidus and the preoptic area), but not others (ventral striatum) (Loup, Tribollet, Dubois-Dauphin, & Dreifuss, 1991). These and other results (Hazan & Shaver, 1987), suggest that pair and parental bonds may have a related biology and both partly be adaptations of simpler Pavlovian reward learning (see also (Bowlby, 1969)). We discuss the case of pair bonding in the Appendix (A), but postpone the extension of our model to this case.

While proximity is rewarding, social separation is punishing in both human and non-human species. Separation can trigger a behavioural and hormonal stress response and augment the stress response to secondary threats or illness (Ainsworth, Blehar, Waters, & wall, 1978; Karen, 1994). While the behavioural stress response typically includes increased proximity-seeking, it includes social withdrawal or 'avoidance' in some individuals. This between-individual variability probably partly reflects a child's prior social experiences and has long puzzled human developmental psychiatrists/psychologists, who consider it a precursor to later social (mal) adjustment (Ainsworth, 1979). Numerous authors argue that prior experience of *controllability* is critical to explaining this diversity (Levine, 1980; Seligman, 1975; Watson, 1979). For example, can the child expect to control parental proximity thereby ending an unpleasant separation? Such parental "responsiveness" or controllability is presumed to explain individual responses to separation in the Ainsworth Strange situation stressor (Ainsworth, 1982; Main & Weston, 1982). Research on non-social behaviour (Amat et al., 2005; Seligman et al., 1971; Seligman, 1972) would also implicate (un)controllability: Prior experience with uncontrollable punishment can drive behavioural passivity or inhibition (Dayan & Huys, 2008; Huys & Dayan, 2009), specifically activating 5 H T/HPA systems[1](Chrousos & Gold, 1992). Because inhibition persists and generalizes at great cost (Amat et al., 2005; Seligman et al., 1971; Seligman, 1972) it has been considered Pavlovian (Dayan & Huys, 2008; Huys & Dayan, 2009). From this view, we might expect the experience of persistent neglect – i.e. uncontrollable separation – to result in socially withdrawn or inhibited behaviour.

### 3.2. Mathematical details: learning the contingencies

The technical assumptions and computational scheme in this section are thoroughly motivated in Section 3.3–3.4.

**Adult's policy** (From contingencies in Fig. 1). Let $q_{t,a}$ denote the probability of reward $r \in \{0,1\}$ given adult type $t \in \{1,...,4\}$ and child's action $a \in \{0, 1\}$ i.e. withdraw or approach. As in Fig. 1 this reward probability $q_{t,a}$ takes two values $'HIGH' = 1 - \varepsilon$ or $'LOW' = \varepsilon$ where $\varepsilon$ is the chance adult deviates from a pure deterministic policy in any one interaction ($\varepsilon = 0$ or $\varepsilon = 0.2$ in different simulations).

**Child's policy.** Formally, child's situation in Fig. 1 resembles a partially observable Markov decision process (POMDP) with the 'state' (Adult's policy) being unknown. Optimal, *goal-directed approach motivation* reflects the relative value of $\delta_o = V(approach) - V(stay)$, where $V(action)$ is the expected value of an action. In our example it can be shown that the child's goal-directed *approach motivation* is

$$\delta_o = (1 - 2\varepsilon)(p_2 - p_1)$$

for an ideal goal-directed child. The first factor captures predictability: $\varepsilon$ is the frequency with which parent deviates from pure (deterministic) predictability. We first fix $\varepsilon = 0$ (i.e. the *LOW* probability of unit reward in Fig. 1 equals 0 and the *HIGH* probability equals 1) then we fix $\varepsilon = 0.2$. The second factor draws on $p_1, ...,p_4$ which represent child's belief about parent's type i.e. the probable controllability of social proximity. Thus goal-directed approach motivation depends on the child's model of the *predictability* and *controllability* of social rewards. We assume that a dopamine-mediated social approach bias $\eta$ changes $V(approach)$ to $V(approach) + \eta$. Conversely, a history of neglect creates a 5 H T-mediated inhibition, effectively changing $V(stay)$ to $V(stay) + s$ in relation to the expectation of uncontrollable separation $s$. Here we assume $s$ is a step function which gives 0 inhibition if $p_3 < 0.75$, otherwise a 1 unit inhibition bias. Together these assumptions imply that the Pavlovian responses linearly bias the child's goal-directed *approach motivation* to give

$$\delta_0^{'} = \delta_0 + \eta - s$$

We further assume that $p_i$ and $\eta$ are learned independently as in models of animal feeding (Dayan et al., 2006), see below. The $p_i$ reflect previous instrumental (action-outcome) experience with a series of adults according to Bayes-optimal learning. Critically these

[1] Controllable stressors in contrast drive sympathetic-adrenomedullary activation.

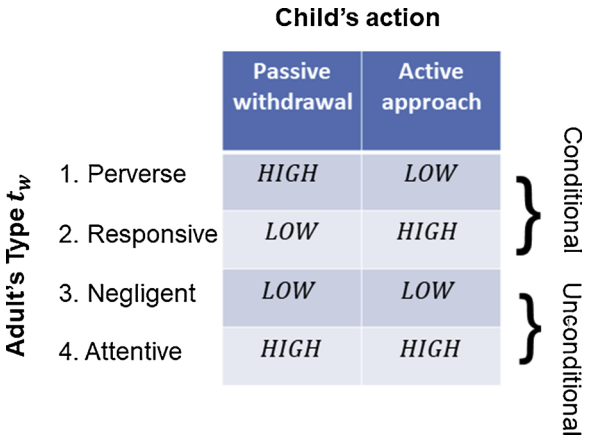


**Fig. 1.** Probability of social proximity depends on adult's type and child's behavior. "Responsive" (type 2) adults specifically reward the child's approach. "Perverse" (type1) adults specifically punish the child's approach. Type 3 and type 4 are "Negligent" or "Attentive", irrespective of the child's behavior: Type 3 incurs uncontrollable separation stress. *LOW* and *HIGH* indicate that the child achieves proximity (and receives unit reward) with probability $\varepsilon$ and $1-\varepsilon$, respectively. See Section 3.2.

include generalization from previous relationships. In contrast, $\eta$ - the strength of the social bonding instinct - simply increases after each rewarding contact according to Pavlovian prediction-error learning (Rescorla & Wagner, 1972) decreasing otherwise. Figs. 1–4 plot the child's approach motivation towards various adult types, for optimal, biased and strongly-biased children: respectively $\delta_0$ , $\delta_0^{'}$ and $\delta_0^{''} = \delta_0 + 2(\eta - s)$.

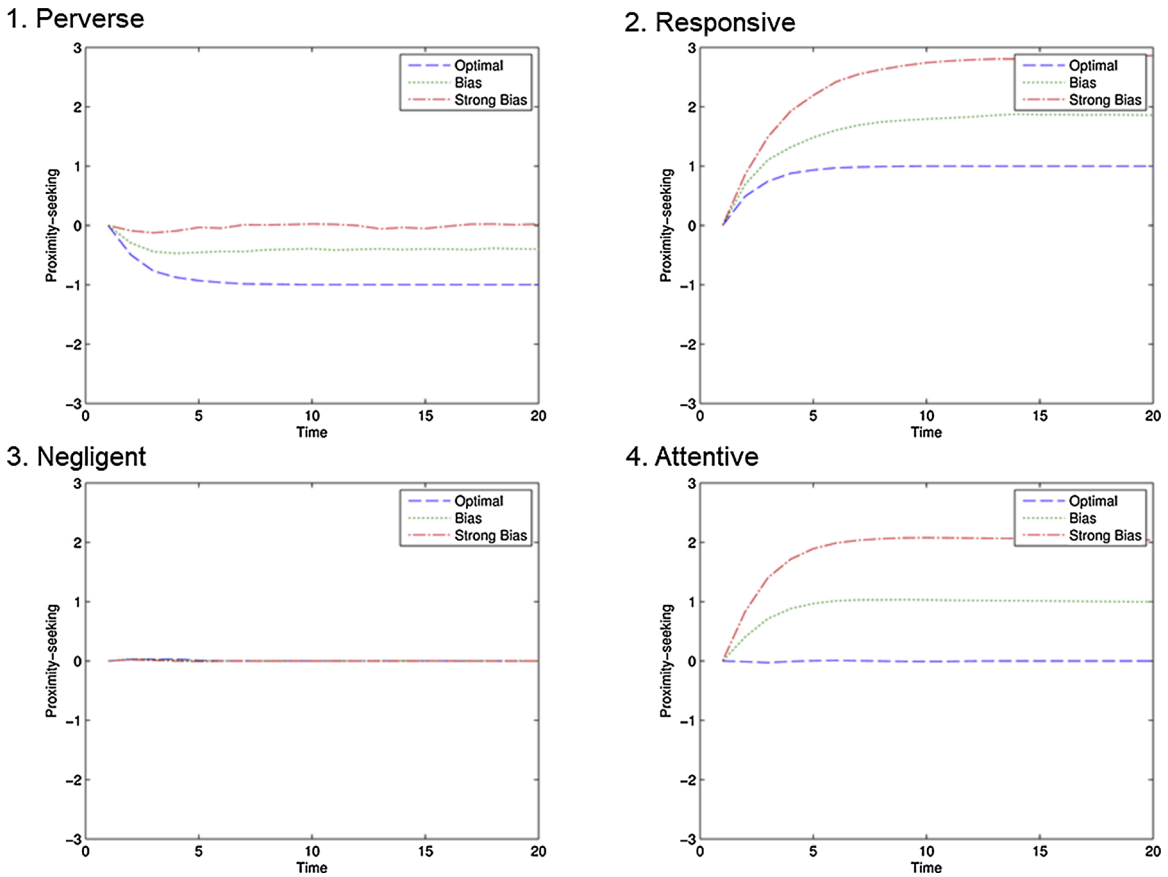


**Fig. 2.** The dynamics of a naïve child's approach towards various types, for optimal, biased and strongly-biased individual. Here each adult has a deterministic policy (i.e. unpredictability $\varepsilon \approx 0$). The left column shows that the child never has positive approach motivation (proximity-seeking) towards to perverse or negligent Adults. The child does however unnecessarily approach Attentive adults.

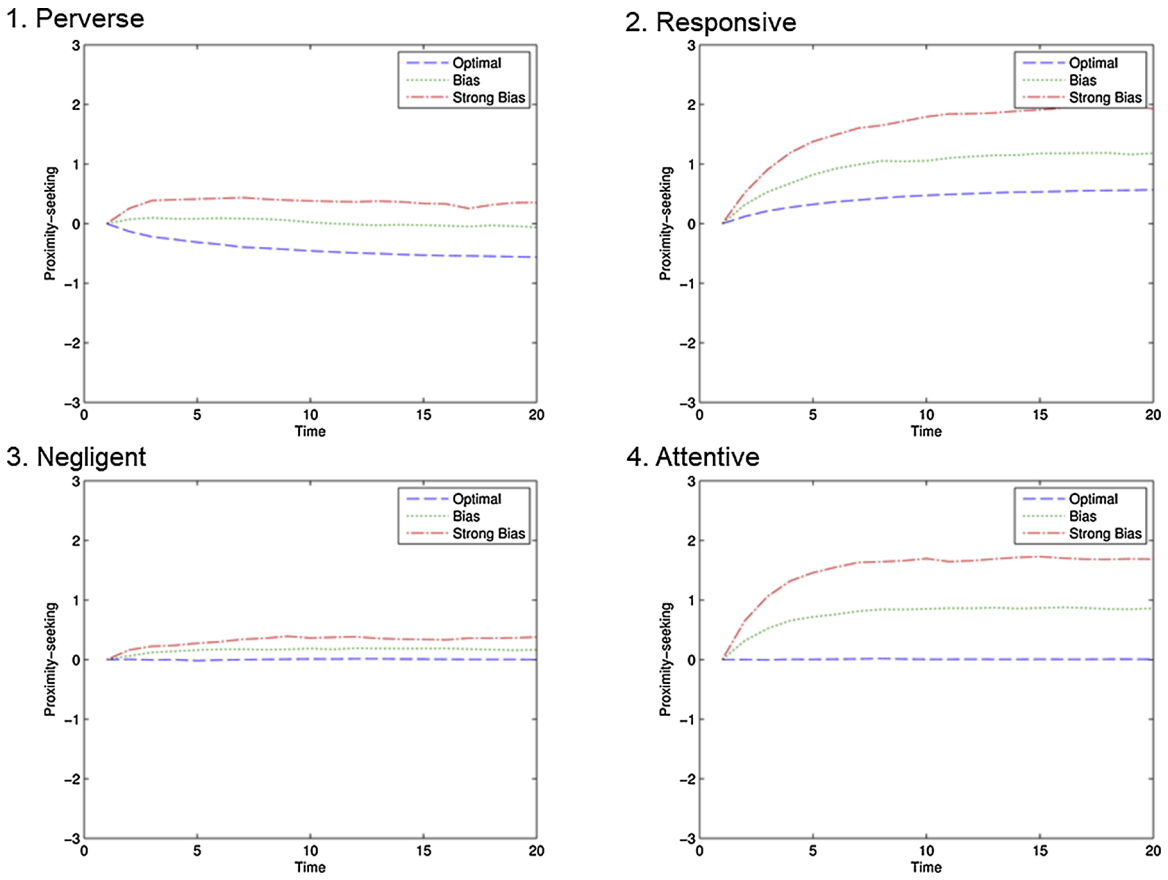


**Fig. 3.** The importance of an unpredictable or erratic adult policy for facilitating a Pavlovian approach bias. These simulations are identical to those in Fig. 2 except that $\varepsilon \approx 0.2$(i.e. unpredictability). The figures show that approach motivation in a naive child increases due to a Pavlovian approach bias. A sufficiently strong bias will ensure that the child always displays positive approach motivation, *irrespective of the quality or type of adult's policy*.

In Fig. 3 $\varepsilon \approx 0$, in all other Figures there is some unpredictability: $\varepsilon = 0.2$.

Based on her experience-dependent beliefs $p_i$ and biases $\eta$, $s$ (described in the appendix) the child makes softmax choices $\sigma(x) = \frac{1}{1+e^{-x}}$. In different plots $x$ takes different values: either optimal $x = \delta_0$, biased $x = \delta_0^{'}$ or very biased $x = \delta_0{''}$, as described in the Appendix (B).

a) **Child's goal-directed learning. i.** Optimal goal-directed behavior requires learning the adult's type in (a) and generalizing them appropriately to strangers. Given $N_{a,w}$ repeated actions $a$ towards adult $w$, the total reward $R_{a,w}$ follows a type- and action-dependent binomial distribution. Notationally, $R_w = (R_{0,w}, R_{1,w})$ is the concatenation of these two random variables for each possible action $a \in \{0, 1\}$ towards a specific adult $w$. In turn, $R$ is the concatenation of $R_w$ over all $W$ adults. Child's belief in adult $w$' s type reflects the likelihood of $t_w$ combined with belief $\theta$, specified as follows. Experience with $W$ adults permits Bayes-optimal learning of the distribution of adult types in the population $p(\theta|R)$ over the 4-vector $\theta$. (We approximate $p(\theta|R)$ by a delta function at it's expectation $\int \theta p(\theta|R)\, d\theta$, which makes this integral trivial.) **ii. Generalizing.** Knowing the probability distribution over types of adult in the population permits optimal generalization: i.e. the best guess of a *new* adult's type $p(t_{W+1} = i|R)$, assuming adults arise as independent samples from the same population. In this way previous relationships optimally guide future expectations.

b) **Child's Pavlovian learning.** Non-instrumental learning ignores the adults' policy in (a). Instead, after each interaction the child's proximity-seeking instinct is updated via Rescorla-Wagner prediction-error. The conditioned approach $\eta$ to a each new adult is initialized to 0 and becomes stronger following reward and weaker following non-reward.

c) **Table of parameters/variables** is provided in the mathematical Appendix (B).

### 3.3. Overview of our basic assumptions

In our simple model, all children innately prefer proximity over separation, but can either actively approach the adult or passively withdraw. The "right" choice depends on the parenting style (see Fig. 1). Critically there are different types of adults, which differ in

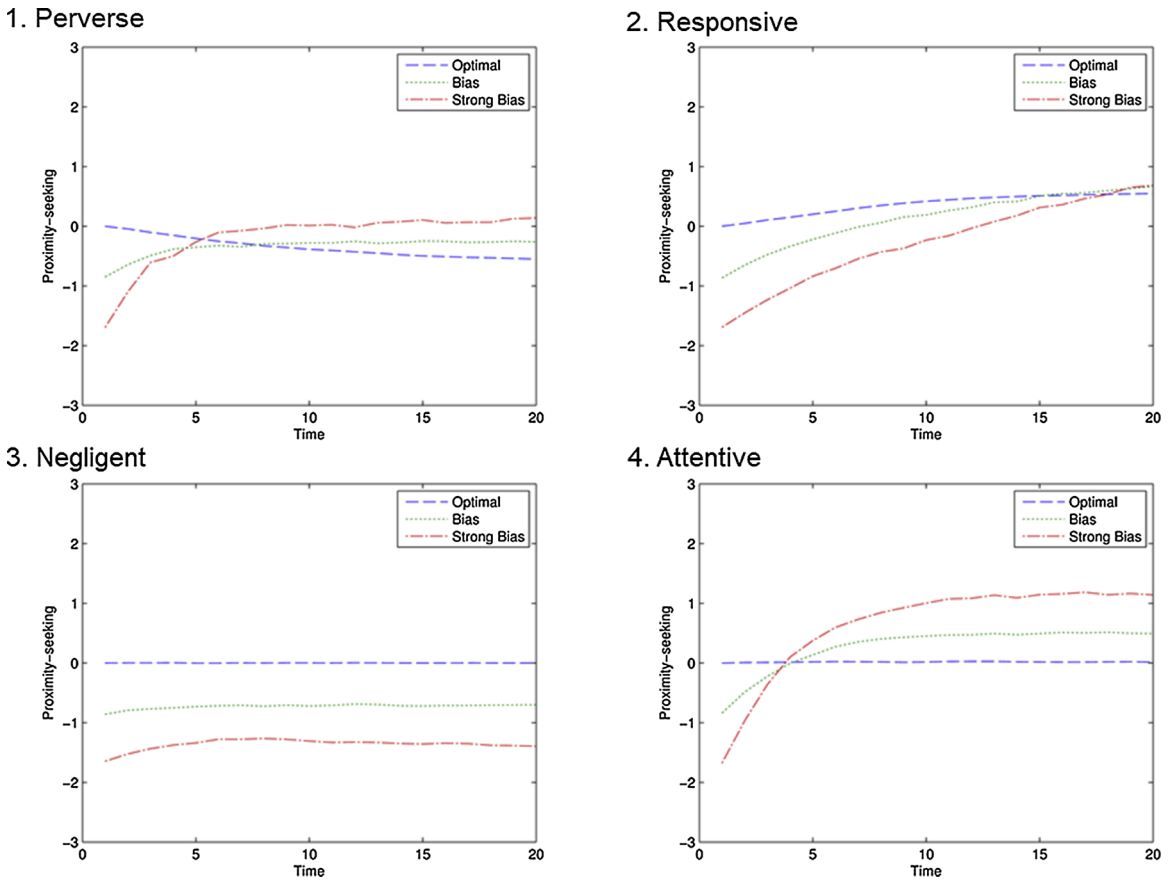


**Fig. 4.** Influence of prior neglect on approach motivation to a new adult. These simulations are identical to those in Fig. 3 except that child has had prior experience of negligent adults. An initial avoidance bias (negative social approach) shows that the child has generalized from past experiences. This withdrawal can be remedied to different degrees, depending on the new adult's type.

terms of how they respond to the child's behavior. There are four types of adults which a child might encounter in our simple and caricatured simulations: 'Responsive' adults reinforce active approaches from the child (permitting social proximity); 'Perverse' adults reinforce withdrawn children, only offering proximity when the child does not initiate it; 'Negligent' adults do not offer proximity, regardless of what the child does; 'Attentive' adults permit proximity, regardless of what the child does. These last two types are both technically uncontrollable – i.e. the adult's behavior is independent of the child's behavior - but we assume that only 'Negligent' adults trigger separation distress in the child, which we model behaviorally as social withdrawal (for details of this *separation distress, see* Section 3.1). This modeling choice is based on the learned helplessness literature, whereby uncontrollable stressors are associated with withdrawal and inhibition and are interpreted as instinctive or Pavlovian responses (see Section 3.1 above).

We consider these adult types, "attachment styles" or "contingencies" (Ainsworth, et al.; Bowlby, 1958; Bretherton, 1985) to be fixed and we focus on how the child responds to them. The child has only one goal – to achieve proximity to the adult - but must achieve this goal differently, depending on the adults "type" or policy, i.e. faced with one of the adult types described above, the child must correctly learn either to approach or withdraw in order to gain proximity, or learn they are unable to influence proximity. Thus, the instrumental solution to this challenge would seem straightforward: a) learn the adult's *type* then b) act accordingly. Our model therefore assumes

1 With experience, a child will learn which reactions to expect from the adult, given the adult's individual policy. If such experience is consistent over multiple adults, partners, or contexts, the child will form increasingly generalized stereotypes about the people they are likely to encounter in life.
2 In principle, the child can exploit these high-level, "model-based" expectations for "optimal" goal-directed (instrumental) social behavior.

Crucially however, inspired by the animal literature on Pavlovian-instrumental interactions (see below), our model for child's behavior makes additional assumptions:

3 The high-level, "model-based" expectations in assumption (1) *can also directly trigger instinctive (Pavlovian) approach or withdrawal behaviors*, i.e. fixed behavioral programs executed without regard for their instrumental consequences.
4 With repeated social exchanges, these Pavlovian responses are independently (of assumption 1) updated according to the usual rules of Pavlov learning.

Depending on the situation, these Pavlovian responses are therefore free to either accord with, or undermine, the child's own instrumental strategy to gain social proximity and contact (as described in assumptions 1,2).

To summarize so far, we model social behavior as a function of both goal-directed and Pavlovian forces, in cognitively sophisticated agents capable of abstraction and generalization. The model-based predictive belief that *should* inform optimal goal-directed behavior incidentally also triggers Pavlovian impulses. It is a prediction of our model that such inner conflict would have both cognitive and behavioral manifestation (Cassidy & Berlin, 1994). Section 3.2. gives mathematical details of the learning and choice. In what follows, we first discuss a purely goal-directed child's behavior (without interference from instinctive behavioral responses) before considering this Pavlovian interference. Throughout we quantify the child's policy in terms of their *motivation to approach* the adult, which may either be positive or negative.

### 3.4. Additional details of the model

The goal-directed child aims to maximize proximity to the adult, given her current beliefs. Specifically, she should approach exactly when this is likely to achieve proximity. It can be shown in our example that the child's *goal-directed approach motivation* depends on their beliefs about the adult's predictability $\varepsilon$ i.e. how often the adult randomly deviates from their policy. The model shows that adult's *predictability* makes the child's approach behaviour less erratic (Huys & Dayan, 2009). Goal-directed approach motivation also depends on the perceived controllability (see mathematical Appendix (B)). If a goal-directed child believes the adult is controllable she will adopt the appropriate response to achieve proximity i.e. withdraw from 'Perverse' adults versus approach 'Responsive' adults (Fig. 1). This happens according to the child's subjective probabilistic belief that the current adult is one or the other of these types, i.e. $p_{RESPONSIVE} - p_{PERVERSE}$. If the child believes the adult is *uncontrollable* (i.e. 'Negligent' or 'Attentive') then she is indifferent between approach and withdrawal (see Appendix (B)). Because belief about the adults' type depends on experience, the child's policy has a time-dynamic.

In parallel to the child's evolving goal-directed policy described above, we posit that the child can also express a simple *Pavlovian approach response* – reinforced with every socially rewarding contact – which compels them to approach the adult, regardless of the wisdom of this impulse. Conversely, the child can express a *Pavlovian inhibitory response* which compels passive withdrawal and is triggered by the expectation of *uncontrollable* separation, regardless of the consequences. This impulse is akin to "learned helplessness" (Seligman, 1972) in that it is driven by exactly the same cognitively sophisticated generalizations underlying exploratory goal-directed behavior that were described in the previous paragraph. In the simulations below, we assume that these experience-dependent Pavlovian responses compete with each other and collectively oppose the goal-directed policy described in the previous paragraph. Thus, experience shapes behavior via multiple dissociable learning systems (Dayan & Niv, 2008), only one of which is strictly goal-directed. In this way, Pavlovian responses can lead bonding behavior to become systematically counterproductive over time, demonstrating both overzealous persistence in early adverse relationships yet generalized withdrawal from future potentially rewarding relationships.

## 4. Results

Fig. 2 shows a naïve child's *approach motivation* towards various adult types over time, for an optimal goal-directed child, a (Pavlovian) biased and strongly-biased child (see Appendix (B)). Here we have fixed adult predictability to 100% so that the adult never deviates from their policy. In this example, the child has no positive motivation to approach 'Perverse' or 'Negligent' adults. A Pavlovian bias increases the child's motivation to approach both 'Responsive' and 'Attentive' adults. The latter is interesting because it serves no purpose: 'Attentive' adults do not require approach as a condition granting proximity. This inefficiency therefore closely resembles the sign-tracking or autoshaping observed in experiments on animal feeding behavior, e.g. (P. Dayan & Niv, 2008).

In Fig. 3 we have relaxed adult's *predictability* to 80% (i.e. 20% of the time adult randomly deviates from their policy). Recall that only one type of adult – the 'Responsive' type – selectively rewards the child's approach. Nevertheless, Figs. 3.1, 3.3 and 3.4 illustrate a general and persistent *approach motivation,* even in the face of neglect or punishment: proximity-seeking increases and persists when it is unnecessary (i.e. 'Negligent' or 'Attentive') or even counterproductive ('Perverse'). Fig. 3 shows that this bias depends in general on adult policy being somewhat erratic or unpredictable. This is because such a policy provides the occasional spurious rewards ('teasing') which classically condition the child to disadvantageously approach. The example illustrates that adult unpredictability supports an approach bias in at least two different ways. To see this, consider the following. If 'Negligent' types were completely predictable, there would be no 'teasing' and therefore no basis for classical conditioning (Fig. 2.3). As we allude above, if 'Perverse' types were completely predictable then a strong, goal-directed motivation to withdraw would overpower the Pavlovian approach bias. The effect of predictability on instinctive behaviour depends: unpredictability decreases approach towards responsive partners but increases it towards perverse types.[2]

[2] This interaction is simply explained by the net number of rewards.

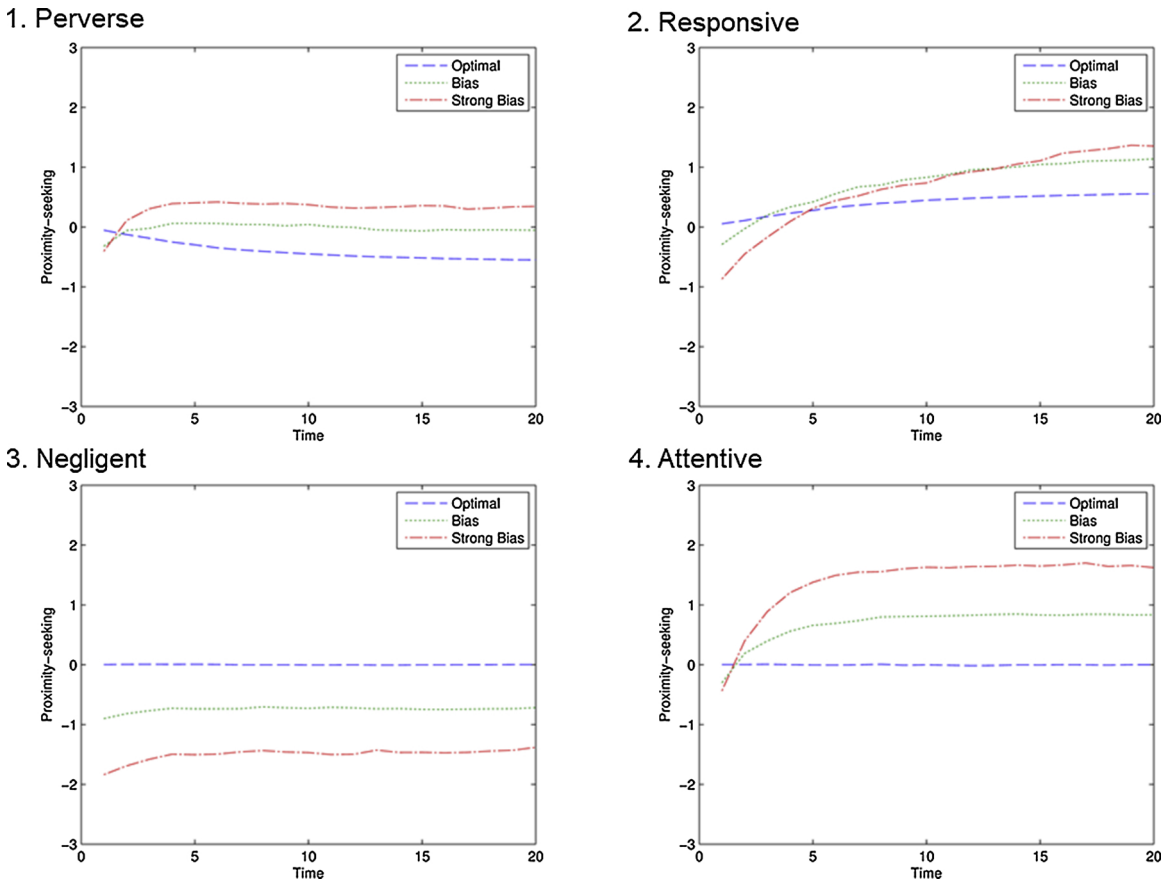


**Fig. 5.** Enduring influence of prior neglect on approach motivation to a new adult. This plots the same variables as other Figures. It particularly shows the response of a previously neglected child to a second partnership with either Perverse, Responsive, Negligent or Attentive. Note that the recovery of proximity-seeking following attentive or responsive partners (see Fig. 4), does not completely transfer to a new partner. This indicates a stable, transferable "style" that enduringly reflects early experience.

Fig. 4 plots how one child's proximity-seeking towards the four different adult types changes in individuals with a history of prior neglect (i.e. extensive prior experience with 'negligent' adults). Such children demonstrate social withdrawal from future partners of all types. This generalized style can eventually be remedied by a new "responsive" or "attentive" partner, a recovery greatly accelerated if subsequent partners are "attentive". However, Fig. 5 shows that such recovery is initially limited and does not substantially transfer to further relationships. This lasting consequence of early life on social bonding provides a tentative model for enduring, experience-dependent attachment styles. The model achieves this pattern of generalized social avoidance through the assumption that people develop rational expectations about the social contingencies they face in the population at large, i.e. a "mental model". For example, a child exposed to systematic early negligence may validly use inductive generalization to conclude that people, *in general,* are negligent. However, these rational expectations do not only motivate goal-directed behaviour, they also trigger involuntary, mischievous Pavlovian responses, such as helplessness or avoidance. In this way, we model maladaptive or suboptimal social behaviour in a manner that resembles the so-called "model-based" Pavlovian responses previously described for the case of nonsocial behaviour (Dayan & Seymour, 2008).

## 5. Discussion

Using social approach and withdrawal as an index, we have begun to examine the robustness of social bonds within and across sequential partnerships. We focused on "persistence" in relationships i.e. the ability of learned approach behaviour to survive protracted non-reinforcement or punishment (Breland & Breland, 1961; Dayan & Niv, 2008; Nation & Woods, 1980). This persistence is relevant to both well-adjusted and clinically maladjusted social behaviour (Teicher et al., 2003)[3]. Persistence may fortify positively reciprocal relationships against error and misunderstanding but can equally open an individual to exploitation from negligent/non-reciprocating partners (Bowlby, 1969). We took a computational perspective to ask how instincts (Bowlby, 1969) might bolster or

[3] Socio-behavioural consequences of early punishing relationships are a risk factor of various psychiatric disorders

undermine this persistence even in cognitively sophisticated individuals (Bowlby, 1969). We specifically modelled how different learning systems interact to shape an individual's history-dependent bonding behaviour. We showed how two history-dependent Pavlovian mechanisms might lead to non-instrumental social behaviour. A history of social rewards reinforced "involuntary" social approach. Conversely, historical punishment, in the form of previous negligent partners, fostered a costly, generalized (Chumbley et al., 2012) social withdrawal. As discussed above, we speculate that these effects be DA and 5 H T-dependent. In our model both self-punitive tendencies are found in individuals with the capacity for goal-directed behaviour and hence full knowledge of the costs. In fact, sophisticated beliefs are partly responsible for these suboptimal tendencies because they trigger incidental, 'model-based' (P. Dayan & Seymour, 2008), Pavlovian responses. The model therefore provides an example of how early social adversity can affect individuals' developmental trajectories (Callaghan & Tottenham, 2016) over time and space (i.e., across varying social contexts).

### 5.1. Correlations among parenting and child attachment behaviors

Our model reproduces, and attempts to mechanistically explain, the empirically documented correlation between parenting practices and children's proximity-seeking behaviors - typically expressions of children's "attachment styles". One longstanding observation is that parent's responsiveness to the child's needs (i.e., appropriately perceiving, interpreting, and swiftly responding to the child's signals and communication), predict the development of "secure" versus "insecure" attachment behaviors in the child. "Secure" attachment behaviors take the form of approaching the mother in order to establish proximity with her (Ainsworth, 1985; de Wolff & van Ijzendoorn, 1997; Cummings & Cummings, 2002; Bigelow et al., 2010). In Ainsworth's "Strange Situation", secure attachment is evidenced when children proactively approach the parent in the moment of reunion (Ainsworth, 1985). The child depicted in panel 2 (Fig. 2) emulates the response of our model to the ideal, sensitive parent who responds appropriately to the child's signaled aim for proximity on the one hand, and abstains as long as the child remains passive (i.e., no *obvious* proximity seeking) on the other. The child's behavioral development indicated in this panel is characteristic of a *secure* attachment style.

In contrast to panel 2, the parenting styles underlying children of panels 1, 3 and 4 (Fig. 2) are incongruent with the child's signaled needs. Empirically, the children of mothers showing lower levels of sensitive responsiveness - as expressed in tenderness/affectionateness - present more "insecure" attachment behavior. This "insecure attachment" has been quantified in the "Strange Situation": namely by lower, or less positive, measures of behavioral approach from the child to the mother on being reunited (Ainsworth, 1985; de Wolff & van Ijzendoorn, 1997; Cummings & Cummings, 2002; Bigelow et al., 2010). The developmental behaviors in panels 1 and 3 mimic the emergence of this *insecure* attachment. More specifically, the pattern displayed in panel 3 typifies child behavior often labeled "*insecure-avoidant*", i.e. not actively approaching - or even ignoring - the mother in the moment of reunion. This behavior is more common towards mothers who themselves express higher levels of rejection toward the child (Ainsworth, 1985). Prior theory argues that such maternal rejection is the root cause: it provokes in the child an "internal working model" of the mother as consistently refusing proximity, no matter what he/she does (see Cassidy & Berlin, 1994, p. 972). Our model therefore formalizes one aspect of this theory.

Underlying the child of Panel 1 (Fig. 2) is a parent who displays a mixture of care and neglect or withdrawal, which are expressed independently of the child's communicated needs. This parenting style caricatures an extreme form of behavior reported in mothers of "*insecure-ambivalent/resistant*" children (Ainsworth, 1985). These mothers "often failed to respond to bids for close contact or offered contact when it was not sought by the baby" (Ainsworth, 1985, p. 777). More specifically, these mothers often appear "unavailable" when their children aim for attention but interfere with their children's autonomous activities when close contact is, in fact, against the child's actual needs (Cassidy & Berlin, 1994). Existing evidence shows that these mothers' children tend to show an angry or conflicted response to the mother's return in the "Strange Situation". By "conflicted" we mean other kinds of attachment behaviors which indicate the inner aim for proximity while at the same time actively resisting it – hence approximating an optimal strategy to gain as much attention as is available (cf. Cassidy & Berlin, 1994).

The parental types we have discussed so far are necessarily simplistic caricatures. The mothers of insecure-ambivalent/resistant children are reportedly still able to respond to their child's signaling in some situations and are also able to enjoy close contact with the child (as opposed to mothers of avoidant children) (Ainsworth, 1985). Hence, this parenting type has also been referred to as "unpredictable" from the child's point of view. In the case of panel 1, it is therefore particularly evident that relaxation of predictability of the mother's policy in step 2 of our model (see Fig. 3) may increase its applicability to "real" situations and, as a result, to existing empirical evidence.

The parent underlying panel 4 (Fig. 2) is indiscriminately attentive, i.e. insensitive to the child's signaled needs. Such over-attentiveness is thought to intrude on the child's need for privacy and autonomy and is one of the most striking characteristics of parenting associated with the insecure/ambivalent type (see also Rothbaum, Rosen, Ujiie, & Uchida, 2002), which we have already discussed in regard to panel 1. In panel 4 however, it is combined with high, rather than low, levels of tenderness when the child actually aims for attention. However, empirical evidence suggests that a combination of high levels of tenderness and low levels of support for children's autonomy will also result in child behavior related to the ambivalent style (Karavasilis, Doyle, & Markiewicz, 2003). Panel 4 may thus be regarded as another extreme parenting practice, and child's response may be conceived of as another variant of what has historically been labeled insecure/ambivalent attachment. In fact, there seem to be different subgroups of insecure/ambivalent children, which differ in their levels of (angry) activity (cf. panel 1, Fig. 2) and passivity (cf. panel 4, Fig. 2) expressed in their attachment behaviors (Cassidy & Berlin, 1994, p. 986). Our model shows that the optimal strategy for a child that aims for proximity with a mother represented in panel 4 would be passivity; however, the (Pavlovian) bias prompts children to approach the mother for the sake of proximity, although this activity is unnecessary. In the case of a highly biased child, proximity seeking behavior can then hardly be distinguished from the secure type.

Model simulations in which Adult behavior is non-deterministic, illustrate clearly how a mismatch between Adult policies and child behaviours may emerge (Fig. 3). The results show that when proximity-seeking is unnecessary or counterproductive, children tend to increasingly approach the parent (Fig. 3.1, 3.3). When parental responsiveness is less reliable, the child's approach motivation is partially diminished (Fig. 3.2). This bears an interesting parallel to the idea that cues which predict uncertainty are possible sources of maladaptation in developing organisms (Frankenhuis & Del Guidice, 2012). Similarly, changes to one's (social) environment (Frankenhuis & Del Guidice, 2012), as modelled in Figs. 4 and 5, make clear how experience in a negligent rearing context can impair later adaptation to more nurturing contexts (e.g., rather slow adaptation to responsive parenting after prior neglect, represented in Fig. 4.2). Figs. 4 and 5 therefore serve as a starting point for understanding the mechanisms that explain consolidation of attachment styles over the life-course, and in particular the potential of sensitive foster care, adoptive families, or therapeutic settings in supporting "earned security" in individuals with a history of prior neglect or maltreatment. The latter is a promising avenue for breaking vicious cycles of attachment insecurity transmitted across generations (see Phelps, Belsky, & Crnic, 1998).

### 5.2. Suggestions for further modeling

Various extensions of our model may help provide further insights into the mechanisms that explain the emergence, the maintenance, and the function (e.g., in terms of a "strategy") of different types and sub-types of attachment behaviors. In practice, empirical researchers may find it challenging to test elaborate extensions, for example, due to low sample sizes in groups of children with variants of the insecure patterns (cf. Cassidy & Berlin, 1994, p. 986). For the sake of our initial presentation, we have focused on the multiple, coupled learning systems known to be at play in any one child. It is implicit that while the child's behavioural policy changes with social learning, the parent's policy does not. This assumption would be approximately true, for example, if a parent's policy toward their child rested on more entrenched generalizations, which have stabilized over a longer life. Alternatively, it would be true if children have a much higher capacity for learning than adults for other innate reasons. If such assumptions appear dubious, they may be relaxed by any extension to our model that embraces simultaneous, dyadic learning dynamics (coupled learning within and between social agents). A related point is that our model places strong bounds on the rationality of both parent and child: the goal-directed social behaviour of a full-fledged *homo-economicus* is based on sophisticated recursive reasoning, i.e. he thinks I think he thinks X, so I will do Y. We have attempted here to avoid the complexities of truly game-theoretic accounts of social bonding, because it is currently unclear to us how this approach might offer a good account of cognition at early stages of development.

We have assumed so far that all individual differences between children are due to learning. For the sake of argument, our model has completely discounted individual differences in the innate personality or attachment style of a child, assuming instead that all children are born with an equivalent generic, hardwired desire and instinct for social proximity, and a capacity to learn. We view this as a null hypothesis, which has allowed us to isolate the purely learned contributions to what has been called the "intergenerational cycle of insecure attachment". Note that the parent behaviours underlying the different panels of our model are themselves typical expressions of respective adult attachment styles (e.g., *autonomous* parents responding to their *secure* children's proximity seeking or *preoccupied* mothers showing unsynchronized responses to their *insecure-ambivalent* children's proximity seeking) (for theoretical and empirical parallels, see Breidenstine, Bailey, Zeanah, & Larrieu, 2011; Rothbaum et al., 2002; van Ijzendoorn, 1995). It will be crucial for future work to assess how the basic capacity for learning interacts with children's differential susceptibility or reactivity to experience, based on a variety of "intrinsic" child characteristics (Belsky, 1997; Klein Velderman, Bakermans-Kranenburg, Juffer, & van Ijzendoorn, 2006).

Finally, the scope of our model is limited to observable behaviors in parent and child (comparable, behavioral, perspectives have been taken to explain, for example, the persistence of some forms of depression, see Trimmer et al., 2015). In order to understand the evolution of different attachment styles in their entirety, and unambiguously differentiate between those styles, it will be important that future extensions of the model elicit how emotional or affective responses of child and parent, and their emotion regulation strategies, factor into the developmental processes under study (see e.g., Groh et al., 2017; Mikulincer & Shaver, 2019). In particular, while our focus was on the interplay between infant cognitive and instinctive impulses that can help explain attachment behaviors, more complete models ought to consider explicitly the emotions that underlie such actions (e.g., sadness, anger, or anxiety), and the emotional comfort that child derives from (body) contacts with the parent (for early empirical evidence see Harlow & Zimmermann, 1959). Going beyond our approach, this would probably involve making assumptions about the *quality* of proximity that is sought for by the child, and provided by the mother. In the light of the empirical evidence, we believe that consideration of the emotional "ingredient" of attachment processes is a crucial next step in preparation of models that eventually aim to test how the mechanics of child's actions vary under differential environmental conditions (e.g., in the face of external stressors) or in the presence of co-existing bonds with several others, or when the aim is to model the persistence of particular attachment bonds over time.

## 6. Conclusions

Our simple model mathematically formulates the clinical value-judgement that some bonding or attachment strategies are *maladaptive*: in particular we explain how exactly 'avoidant' or 'resistant-ambivalent' styles might deviate from (decision) optimality. The model also provides a mechanism to explain suboptimality: it shows how experience can result in a generalized and enduring attachment style that nonetheless changes throughout the life course. While this work heavily simplifies reality, we believe it to be a first step toward quantitative theories in this field: It parsimoniously relates extreme psychiatric behaviors to normal social instincts

and to a wealth of literature on Pavlovian responses; it rigorously defines 'maladaptive' behavior and therefore provides a culturally-invariant and objective quantification of 'unhealthy' socio-behavioral patterns; and, it paves the way for detailed bridging-theories which couple neuronal learning models to higher level psychological models favored in developmental psychology.

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## Appendix A. Pair Bonding

A rich example of social bonding is found in mating-induced heterosexual pair-bonds, where the most developed model is the monogamous prairie vole. Here partner-preferences arise through a process resembling reward learning (Young & Wang, 2004). Mating is rewarding (Becker, Rudick, & Jenkins, 2001; Kelley & Berridge, 2002; Pfaus, Kippin, & Centeno, 2001) and increases nucleus accumbens dopamine (DA), known for its role in "prediction-error" reward learning (Schultz et al., 1997; Schultz & Dickinson, 2000). DA presence in the nucleus accumbens is required for pair-bonding (Aragona, Liu, Yu et al., 2003; Aragona, Liu, Curtis, Stephan, & Wang, 2003; Gingrich, Liu, Cascio, Wang, & Insel, 2000). In this model, the partners olfactory signature predicts sexual rewards and therefore comes to trigger social approach (Young & Wang, 2004). (Rats also develop a conditioned preference for the chamber where they copulated (Everitt, 1990; Paredes & Alonso, 1997) which depends on Nucleus accumbens DA (Pfaus & Phillips, 1991). Such bonding is facilitated by neuromodulatory hormones e.g. oxytocin, whose receptors densely occupy nucleus accumbens. Importantly, nucleus accumbens is specifically involved in the expression of innate, reflexive (Pavlovian) behaviours (Balleine & Killcross, 1994; Berridge & Robinson, 1998; Berridge, 2007; Boureau & Dayan, 2010; Corbit & Balleine, 2003; Hall, Parkinson, Connor, Dickinson, & Everitt, 2001; Ikemoto & Panksepp, 1999; Killcross, Robbins, & Everitt, 1997; Mogenson, Jones, & Yim, 1980; Panksepp, 2004; Parkinson, Willoughby, Robbins, & Everitt, 2000; Reynolds & Berridge, 2001; Salamone & Correa, 2002; Sesack & Grace, 2009; Talmi, Seymour, Dayan, & Dolan, 2008) but not goal-directed (Balleine & Killcross, 1994; Corbit, Muir, & Balleine, 2001) or habitual behaviours (Reading, Dunnett, & Robbins, 1991; Robbins, Giardini, Jones, Reading, & Sahakian, 1990). This makes it a candidate substrate for a relatively inflexible 'innate attachment behavioural system'.

## Appendix B. Mathematical Appendix (see Section 3.2)

a) Goal-directed learning.

i

i ***Infer adult type:*** $\boldsymbol{p_i = p(t = i|history)}$.

$$p(t_w R) \propto \int p(R_w t_w) p(t_w|\theta) p(\theta R) d\theta$$

*where*,

$$p(t_w|\theta) = \prod\nolimits_{t\in\{1,\ldots,4\}} \theta_t^{I(t_w=t)}$$

$$p(R_w t_w) = \prod\nolimits_a Bin(R_{a,w}|N_{a,w}, q_{t,a})$$

$$p(\theta R) \propto p(\theta) \prod\nolimits_{w=1}^{W} \left[ \sum\nolimits_{t=1}^{4} p(R_w t_w) p(t_w|\theta) \right]$$

ii ***Generalize.***

$$p(t_{W+1}|R) = \int p(t_{W+1}\theta) p(\theta R)$$

b) **Pavlovian learning.**

$\eta \longleftarrow \eta + \kappa(r - \eta)$, separately for each $w$

c) **Table of parameters/variables** (Table B1).

**Table B1**
Parameters/variables in the model.

| Name | Interpretation | Setting |
|---|---|---|
| $\kappa$ | Child learning rate | 0.4 |
| $q$ | Parent predictability | 1.5 |
| $\theta$ | Frequency of types | *Learnt* |
| $t_w$ | Type of parent $w$ | *Learnt* |
| $R_{a,w}$ | # Rewards following action $a$ to parent $w$ | *Learnt* |
| $R_w$ | $(R_{passive,w},\ R_{active,w})$ | *Learnt* |
| $R$ | $(R_1,\ ..., R_W)$ | *Learnt* |

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